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A METHOD OF STABILIZING AUTOMATIC REGULATION SYSTEMS

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/Figures are appended./

This article describes a method of conditional stability to improve and stabilize characteristics of automatic regulation systems. It considers an electronic voltage regulator for a generator with stepped up frequency and a power synchronous follower system. The adaptation of circuits for which the provisions of conditional stability are fulfilled made it possible, in both cases, to secure quicker acting systems than with ordinary methods of stabilization and flexible feedbacks.

The utilization of the phenomenon of conditional stability is considered for the stabilization and improvement of the operating qualities of regulating devices. The occurrence of conditional stability is such that the given regulation system has, in its open state at certain frequencies, an amplification coefficient larger than unity, with a phase angle displacement of the output voltage in relation to the input voltage of 180°, and remains stable. The Nyquist curve for this system has a characteristic "beak." The possibility of a conditional stability was mentioned for the first time in the work of Peterson, Kreer, and Weir. However, this occurrence was not utilized in practice in developed systems of automatic regulations.

Until recently, conditional stability was considered as of theoretical interest, but hardly to be employed in practical systems. However, the two following examples show the utilization of conditional stability to stabilize a system of regulation and to improve its operating qualities. The first examines the stability of an electronic voltage regulator for a generator with stepped up frequency of 800 cps and power of 2 kw.

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Figure 1 shows a diagram of an electronic voltage regulator. The measuring element of the regulator consists of a nonlinear bridge, three arms of which have fixed resistances, while in the fourth arm there is a diode 4D2 with a tungsten cathode, having a stable emission, whose filament is fed by the regulated voltage. The diode resistance depends on the filament current magnitude. During voltage fluctuation of the generator, voltage appears at the output of the measuring bridge whose polarity and magnitude depend on the direction and amount of displacement of the generator voltage from the assigned value, corresponding to the balance of the nonlinear bridge. The voltage from the output of the measuring element is applied to the grid of the tube Л_3(6H7), which is connected in the phase bridge circuit.

With a voltage fluctuation on the grid of tube Л_3, its equivalent resistance changes too, which results in a voltage phase displacement on the grids of the thyratrons, relative to the voltage on the anodes of the thyratrons Л_4 and Л_5 (TГ -213). The rectified voltage, whose value depends on the voltage deviation of the generator, is applied to the excitation winding of the generator. The entire regulator is supplied by the generator voltage at a frequency of 800 cps.

A block diagram of the regulator is illustrated in Figure 2 and, as demonstrated by the tests conducted, can be represented in the first approximation in the form of three links: (1) link measuring element, (2) link amplifier and power elements, and (3) link generator. All three links can be replaced by equivalent inertia elements described by operators of the form $\frac{K_1}{1+pT_1}$ with time-constants T_1, T_2, T_3, and amplification coefficients K_1, K_2, K_3. Inasmuch as all regulator elements are elements of directed operations, i.e., the operations in each successive link of the regulator do not influence the preceding link, to obtain the general equation of the system in an open state, it is sufficient to cross-multiply the operators corresponding to each link. As a result we obtain

$$U_{out} = -U_{in}\,\frac{K_{13}}{(1+pT_1)(1+pT_2)(1+pT_3)}, \qquad (1)$$

where T_1, T_2, T_3 are time-constants of the separate regulator links, $K_{13} = K_1$, K_2, K_3 -- over-all coefficient of amplification, equal to the products of the amplification coefficients of separate links, and p is the differential operator. In a closed circuit of regulation

$$U_{in} = U_{out} \qquad (2)$$

Substituting (2) in (1), we obtain, after corresponding transformations, the characteristic equation

$$a_0 p^3 + a_1 p^2 + a_2 p + a_3 = 0, \qquad (3)$$

where

$$\left.\begin{aligned} a_0 &= T_1 T_2 T_3, \\ a_1 &= T_1 T_2 + T_2 T_3 + T_1 T_3, \\ a_2 &= T_1 + T_2 + T_3, \\ a_3 &= 1 + K_{13}. \end{aligned}\right\} \qquad (4)$$

Equation (3) is the characteristic equation, corresponding to the differential equation of the regulation system in question. Setting up Hurwitz' condition for stability and substituting values obtained experimentally for T_1, T_2, and T_3 (T_1 = 0.1 sec, T_2 = 0.01 sec, T_3 = 0.35 sec,) we shall find the limiting coefficient of amplification of the system at which stable operation of the regulator is still possible without the introduction of anti-hunt devices:

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$$1+K_{lim} \leqslant (T_1+T_2+T_3)\left(\frac{1}{T_1}+\frac{1}{T_2}+\frac{1}{T_3}\right) \qquad (5)$$

Or after substitution of values for T_1, T_2, and T_3:

$$1+K_{lim} \leqslant 52 \qquad (6)$$

The actual amplification coefficient is equal to 600; therefore, one has to expect that in the absence of antihunt devices the regulator will be unstable. This is confirmed by the oscillogram in Figure 3, which illustrates that the regulator produces undamped oscillations.

To achieve stable operation of the regulator, it is necessary to introduce in the regulation system an antihunt element, which, taking into consideration the requirements presented to the regulator, should be simple. Besides, it is desirable that the absence of sustained oscillations is not attained at the expense of a considerable decrease of the amplification coefficient, or at the expense of considerable decrease in the speed of regulation. In the given case, while investigating the characteristics of the system, it is expedient to use Nyquist's method of amplitude-phase characteristics, inasmuch as this shows graphically the influence of one or another antihunt devices on the regulation stability. For plotting the amplitude-phase characteristics it is necessary to substitute $p = j\omega$ in the expression for the operator of the open system $K = f(p)$ and to lay out the curve $K = f(j\omega)$ with ω changing from 0 to ∞. The second branch for ω changing from 0 to $-\infty$ will represent a reflected image of the first, relative to the real axis in the plane, f. If, in addition, the point (1, j0) lies inside of the obtained curve, then the system will be unstable; if outside of the curve, it will be stable. From (1) the operator of the open system of regulation equals:

$$K=\frac{U_{out}}{U_{in}}=-\frac{K_{13}}{(1+pT_1)(1+pT_2)(1+pT_3)} \qquad (7)$$

The amplitude phase characteristic for an open system, described by equation (7), with the above indicated parameters, is illustrated in Figure 4, curve 1.

Inasmuch as the point (1,j0) lies inside the curve, the regulator is unstable. The natural frequency of the sustained oscillations of such a system corresponds, approximately, to a frequency at which the characteristic intersects with the positive axis x. In the case considered, ω equals approximately 40, which conforms quite well with the experiment (Figure 3).

There are two basic methods for clearing the oscillations.

The first and most perfected method consists of inserting derivatives from the regulated parameter into the regulation circuit. In practice, with ordinary systems one usually is limited to the first derivative. The second method consists of changing the adduced time constants, at the expense of introducing the induction into the regulation circuit a flexible feedback. This method of eliminating sustained-oscillation is not as good as the first one, since the time of the transitional process usually increases. The illustrated block diagram of a regulator in Figure 2 gives only small possibilities of introducing antihunt devices with the stipulation that resulting circuit complications are negligible. One of the reasons for this is the impossibility for constructive considerations of introducing the feedback voltage into the measuring element of the regulator to utilize its amplification coefficient for the feedback voltage as well. Therefore, a more expedient regulator scheme with an antihunt element is illustrated in Figure 5, where element IV is an element producing a voltage at the output proportionally derived from the input voltage.

The schemes considered for element IV give a distorted derivative with an inertia characterized by the time constant T.

Figure 6 illustrates the circuit for element IV. The sum of the voltages taken from the nonlinear bridge and from the resistance R_1 is applied to the input of the amplifier element. The value of the resistance R_1 should be a few times larger than the resistance introduced by the bridge, so that the circuit $R_1 - C_1$ can be considered a link of directed operations. The voltage, taken from the output of element IV is equal, according to Figure 6, to:

$$U_{out} = -\frac{pT_4}{1+pT_4} U_{in} \qquad (9)$$

where

$$T_4 = R_1 C_1 .$$

With a parallel connection of element IV and element I, the resulting voltage at the output of both elements relative to the voltage of the input - U_{in} is expressed:

$$U'_{out} = -\frac{K_1}{1+pT_1} + \frac{pT_4}{1+pT_4} U_{in} \qquad (10)$$

From (10), it follows that with supplementary undistorted amplification of the voltage taken off the differentiating circuit by K_1 times and with equality of time constants $T_1 = T_4$

$$U'_{out} = K_1 U_{in} , \qquad (11)$$

i. e., in this case, with the help of the parallel connection of the differentiating link, the time constant of the inertia element can be reduced to zero. However, the introduction of supplementary amplification of the voltage taken from element IV would considerably complicate the regulator circuit. Meanwhile, in the absence of such an amplification, the introduction of element IV cannot have significant influence on increasing the stability of the system, since the inertia element has a relatively large amplification coefficient ($K_1 = 15$). The curve in Figure 7 illustrates the amplitude phase characteristic of the measuring element. Curve II is the amplitude phase characteristic of elements I and II in parallel. The equation for the amplification coefficient of the system with the presence of element IV is:

$$\overline{K} = -\left(\frac{K_1}{1+pT_1} + \frac{pT_4}{1+pT_4}\right)\frac{K_2 K_3}{(1+pT_2)(1+pT_3)} . \qquad (12)$$

Corresponding to this equation, the amplitude-phase characteristic of the entire regulator is illustrated in Figure 4, curve II. The introduction of circuit IV, although the system approaches a somewhat stable condition, does not lead to a full elimination of the sustained oscillations, as is confirmed by the oscillogram in Figure 3 where the sustained oscillations of the system were taken with circuit IV in the regulation circuit. Since the above-introduced stabilization method was found to be insufficiently effective for the given regulator, another method was adopted.

Inasmuch as the inertia and differentiating elements are equivalent to certain electric systems with inductances, capacitances, and resistances, one can select a combination of elements which would be equivalent to the resonance conditions for the currents in the electrical circuit for the natural frequency of oscillation of the system. For this, it is apparently necessary that in the expression for the amplification coefficient of the system in a complex form (after substituting $p = j\omega$) the imaginary part approaches zero at $\omega = \omega^o$, where ω^o is the natural frequency of oscillation of the system. To give the resonance curve a sufficiently sharp form, it is also necessary that the real part be sufficiently small.

As shown by the calculations, a series connection of the two inertia links of directed operations, shunted by a differentiating element, as in Figure 9, with certain values of the parameters (T_1, T_5, T_4, and K_1), is equivalent to the condition of resonance for the currents in the electric circuit at $\omega = \omega^o$.

In addition, the phase of the amplification coefficient vector changes abruptly toward the leading side, as ω approaches ω^o. The result is that point (1, j0) is not within the amplitude-phase characteristic, and the system becomes conditionally stabilized. Generally, the analytical calculation of the parameters T_4 and T_5 for given values of T_1 and K_1 is difficult. Therefore, it is expedient for every considered system to select parameters T_4 and T_5 by means of several approximations. The approximation is facilitated by the fact that the values T_4 and T_5 are not of a critical nature, and can lie within a fairly wide range. For the considered system the following values were chosen:

$$T_4 = 0.5 \text{ sec.}, \quad T_5 = 0.1 \text{ sec}$$

The amplitude-phase characteristic of the measuring element, in the presence of only the supplementary inertia element with time-constant T_5, is indicated in Figure 7, curve III. The amplitude-phase characteristic of the regulator on the whole is determined by the expression

$$\overline{K} = -\frac{K_{13}}{(1+pT_1)(1+pT_2)(1+pT_3)(1+pT_5)} \tag{13}$$

and indicated in Figure 4, curve III. The introduction of only one supplementary inertia link with the time-constant $T_5 = 0.1$ sec aggravated, as was to be expected, the stability conditions of the system. The oscillogram of the sustained oscillation of the system, corresponding to curve III in Figure 4, is illustrated in Figure 10.

Curve IV in Figure 7 corresponds to the amplitude-phase characteristic of the measuring element with the introduction of element IV, in addition to the supplementary inertia element. The expression for the operator of the system in an open condition will be, in this case:

$$\overline{K} = -\left[\frac{K_1}{(1+pT_1)(1+pT_5)} + \frac{pT_4}{1+pT_4}\right]\frac{K_2K_3}{(1+pT_2)(1+pT_3)} =$$

$$= -\frac{K_{13}(1+pT_4) + K_2K_3T_4(1+pT_1)(1+pT_5)p}{(1+pT_1)(1+pT_2)(1+pT_3)(1+pT_4)(1+pT_5)}. \tag{14}$$

Curve IV in Figure 4 corresponds to the amplitude-phase characteristic of the system, according to equation (14) with $p = j\omega$. In this case, point (1, j0) proved to be outside of the amplitude-phase characteristic, i. e., the regulator will be stable (the case of conditional stability).

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The oscillogram in Figure 11, corresponding to the connection and disconnection of full load on the generator, shows that the regulator functions with full stability. The time of the transitional process is set for 0.1 sec.

An interesting conclusion from the above-indicated analysis is the possibility of obtaining stable operation of the regulator by means of a distorted derivative and a supplementary inertia link, producing a sharp phase change of the vector of the amplification coefficient toward the leading side, for a frequency approaching the natural frequency of oscillation of the system.

This method guarantees a large amplification coefficient at low frequencies, and makes it possible, consequently, to obtain a quicker acting system than with ordinary stabilization methods through flexible feedbacks. Thus, the method of conditional stability contrasts favorably with the stabilization methods using flexible feedbacks.

As the second example, where the conditional stability is utilized for improving the quality of regulation, let us examine briefly the synchronous follower system with amplidyne control, whose equivalent diagram in an open condition is illustrated in Figure 12. The first phase-amplifier element can be analyzed roughly as an inertia element with time-constant T_1 and amplification coefficient K_1. The amplidyne, with its full compensation, can be approximately represented in the form of two combined elements series of directed operations, corresponding to the control circuit, including the electronic scheme and circuits of the quadrature axis of the amplidyne with an over-all amplification coefficient of K_{23}, and the time-constants T_2 and T_3 (time-constant T_2 is determined together with the electronic tube, in whose anode circuit is connected the control winding of the amplidyne). The fourth element represents the driving motor and is substituted for, in the first approximation, by an inertia element with the time-constant T_4 and the amplification coefficient K_4 (we shall disregard the inductance of the armature circuit). The fifth element is an integrating one. The operator of the system in an open state is expressed by

$$\overline{K} = -\frac{\varphi_2}{\varphi_1} = -\frac{K}{p(1+pT_1)(1+pT_2)(1+pT_3)(1+pT_4)}. \qquad (15)$$

The numerical values of parameters for the system in question are the following: $K = K_1 \cdot K_{23} \cdot K_4 \cdot K_5 = 1375 \cdot 30 \cdot 1.5 \cdot 0.002 = 124$; $T_1 = 0.03$ sec, $T_2 = 0.015$ sec, $T_3 = 0.03$ sec, $T_4 = 0.09$ sec.

Substituting in (15) $p = j\omega$, we shall construct the amplitude-phase characteristic for the considered system. The amplitude-phase characteristic is shown in Figure 13, curve I. Since the point $(1, j0)$ lies inside the curve, the system is unstable. To stabilize the system, a flexible feedback is utilized from the output of the motor (voltage is taken off, proportional to the angular velocity of the motor) through the differentiating element, as in Figure 6, to the input of element II. The system of elements, with flexible feedback, is illustrated in Figure 14. The equation for differentiating element VI will be:

$$U_{os} = -\omega \frac{K_6 p T_6}{1 + p T_6}. \qquad (16)$$

The equation for the elements encompassing the flexible feedback, according to Figure 14, will be

$$\omega = -U_1 \frac{K_{23} K_4 (1 + pT_6)}{K_{rel} K_{os} pT_6 + (1 + pT_2)(1 + pT_3)(1 + pT_4)(1 + pT_6)}, \qquad (17)$$

where $K_{os} = K_{23} K_4 K_6$, and K_{rel} = the coefficient, characterizing the relative value of voltage, taken from resistance R in Figure 6, utilized for stabilization. The expression for the operator of the system in an open condition with flexible feedback, encompassing elements II, III and IV, has the form:

$$\bar{K} = -\frac{K(1 + pT_6)}{p(1 + pT_1)(1 + pT_2)(1 + pT_3)(1 + pT_4)(1 + pT_6) + K_{rel} K_{os} p^2 T_6 (1 + pT_1)} \qquad (18)$$

The amplitude-phase characteristic, corresponding to equation (18) at $K_{rel} = 0.2$, $K_{os} = 24$ and $T_6 = 0.5$ sec, is illustrated in Figure 13, curve II. As the drawing shows, the system, at the given value of $K_{rel} = 0.2$ becomes stabilized. To increase the margin of stability, it is necessary to increase somewhat the value of coefficient K_{rel}. If in place of the differentiating element of Figure 6 we substitute a flexible feedback element, whose circuit is illustrated in Figure 15, the amplitude-phase characteristics of the system will change. If, in the circuit of Figure 15, we assume that the value of resistance R_2 is large in comparison with R_1, we obtain roughly:

$$U_{os} = -\omega \frac{K_{rel} K_6 (p^3 + a_1 p^2)}{p^3 + b_1 p^2 + b_2 p + b_3}, \qquad (19)$$

where

$$a_1 = \frac{1}{T_L}, \quad b_1 = \left(\frac{1}{T_L} + \frac{1}{T_2}\right), \quad b_2 = \frac{1}{T_L}\left(\frac{1}{T_1} + \frac{1}{T_2}\right), \quad b_3 = \frac{1}{T_L T_1 T_2}.$$

$$T_L = \frac{L}{R_1} = 0.25\ \text{sec} \quad T_1 = R_1 C_1 = 0.32\ \text{sec} \quad T_2 = R_2 C_2 = 0.5\ \text{sec}$$

The over-all operator of the system with the presence of the element corresponding to Figure 15 in the flexible feedback circuit is expressed:

$$\bar{K} = -\frac{K(p^3 + b_1 p^2 + b_2 p + b_3)}{p(1 + pT_1)(1 + pT_2)(1 + pT_3)(1 + pT_4)(p^3 + b_1 p^2 + b_2 p + b_3) + K_{rel} K_{os} p (1 + pT_1)(p^3 + a_1 p^2)} \qquad (20)$$

and the amplitude-phase characteristic corresponding to it for $K_{rel} = 0.2$ is illustrated in Figure 16, curve I. For comparison, an amplitude-phase characteristic, curve II, is indicated with an ordinary layout for the differentiating element in the flexible feedback circuit, Figure 6. As can be seen, changing the layout of the flexible feedback circuit brought conditional stability to the system. The difference of curve I from curve II is due to the large amplification coefficient of the system at small frequencies, and a system such as this will be quicker acting. Actually, if we calculate the amplitude of the error for a closed system during a variation in the input parameter (angle) according to "sine" law with an amplitude of 15° and a period of 4 sec, then, for a modified system of flexible feedback, Figure 15, it will be equal to $\sim 2°$; and for an ordinary system (Figure 6) $\sim 4°$, i. e., twice as large. In regard to the part of the curve in the frequency region which characterizes a stable system, it remains approximately unchanged.

Therefore, in the second example, the operation of the system in the area of conditional stability permitted an increase in the rapidity of action of the system. The two above-illustrated examples of regulation systems are taken from experience. The indicated systems operate normally and do not show any operational deficiencies. However, in contrast to other ordinary systems, one has to take into consideration that during the utilization of conditional stability, the decrease of the amplification coefficient below a fixed limit can produce sustained oscillations. The stabilization method for automatic regulation systems employing conditional stability cannot be called a universal method, adaptable for all systems. However, in many cases it permits achievement of a stable system of regulation while preserving its inherent rapid action.

[Appended figures follow:]

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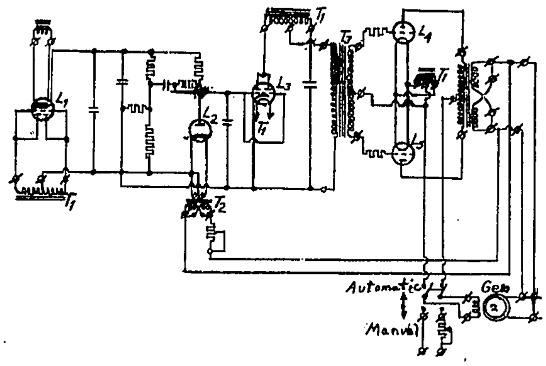
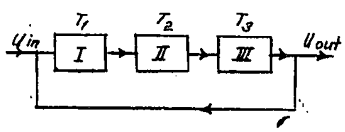


Figure 1. Principle Schematic Diagram of an Electronic Voltage Regulator

Figure 2. Block Diagram of Regulator



I-Measuring element, II-amplifying and power elements, III-generator

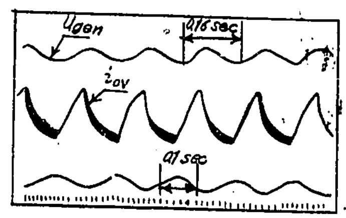


Figure 3. Oscillogram of Sustained Oscillation of a Thyratron Regulator without Antihunt Devices
[Note: i_{ov} is apparently the "relative value"]

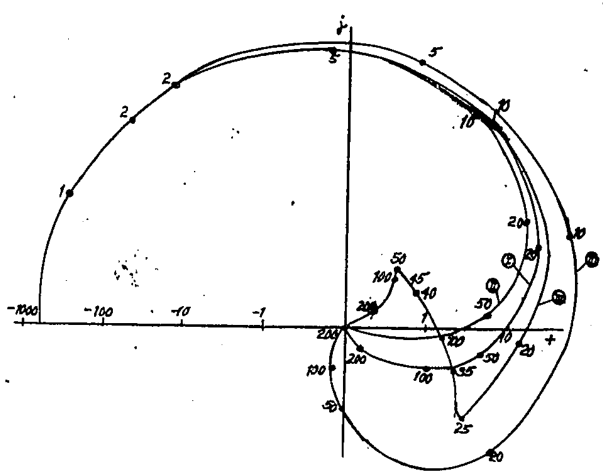


Figure 4. Amplitude-Phase Characteristics of an Open System of Regulation

I -- Without antihunt devices
II -- With the presence of one differentiating element
III -- With the presence of one supplementary inertia element
IV -- With the presence of one differentiating element and one supplementary inertia element

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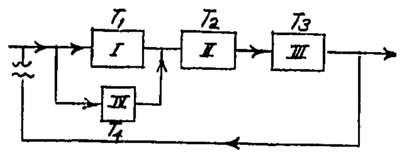

Figure 5. Block Diagram of a Regulator with Antihunt Element

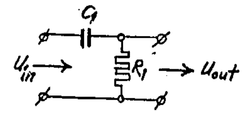

Figure 6. Circuit of a Differentiating Element

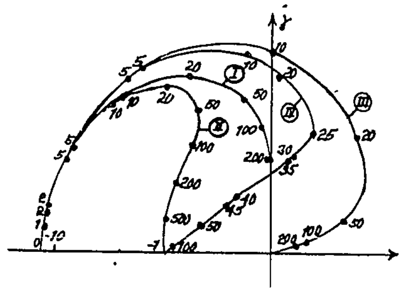

Figure 7. Amplitude-Phase Characteristics of the Measuring Element of the Regulator

I -- Without antihunt devices
II -- With the presence of one differentiating element
III -- With the presence of one supplementary inertia element
IV -- With the presence of a differentiating element and one inertia element

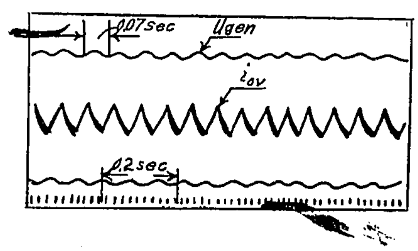

Figure 8. Oscillogram of Sustained Oscillations of Regulator with Introduction into the Circuit of an Antihunt Circuit Conforming to Figure 5

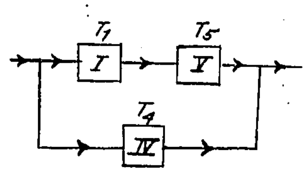

Figure 9. Block Diagram of the Measuring Element of the Regulator with the Presence of Differentiating and Supplementary Inertia Elements

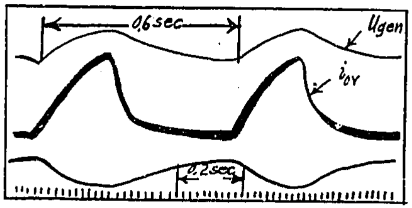

Figure 10. Oscillogram of Sustained Oscillations of a System With One Supplementary Inertia Element

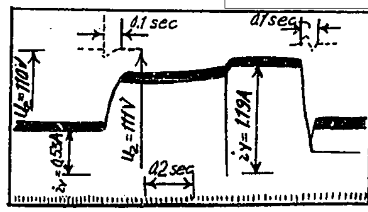

Figure 11. Oscillogram, Corresponding to Connection and Disconnection of Full Load on the Generator

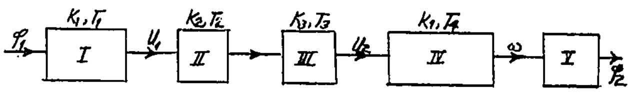

Figure 12. Block Diagram of a Synchronous Follower System with Amplitude Control, in Open Condition:

I -- Phase-amplifier; II and III -- Amplidyne, approximately characterized by two elements of directed operation; IV -- Driving motor, approximated by an inertia element; V -- Integrating element

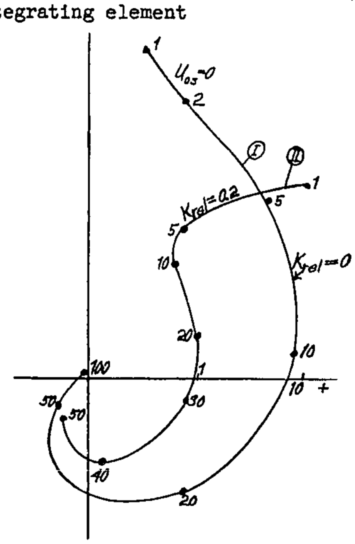

Figure 13. Amplitude-Phase Characteristic of a Synchronous Follower System with Amplidyne Control, in an Open Condition

I -- Without flexible feedback
II -- With flexible feedback

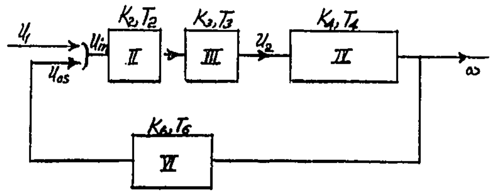

Figure 14. Block Diagram through the Differentiating Element of Flexible Feedback Encompassing an Amplidyne (elements II and III) and Driving Motor (element IV)

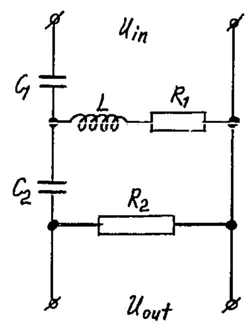

Figure 15. Circuit of Modified Differentiating Element

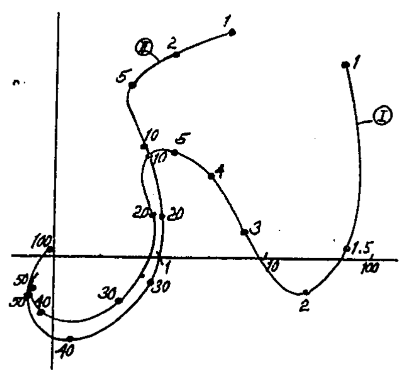

Figure 16. Amplitude-Phase Characteristic of Synchronous Follower System with Amplidyne Regulation in an Open Condition

I -- With flexible feedback, with modified differentiating element
II -- With flexible feedback, with ordinary differentiating element

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